THE NEAR-INFRARED NAI DOUBLET FEATURE IN M STARS *

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* Observations collected at the European Southern Observatory, ESO, La Silla, Chile

Abstract. The NaI near-infrared feature has been used to indicate the dwarf/giant population in composite systems, but its interpretation still is a contentious issue. In order to try to understand the behavior of this controversial feature, we study the spectra of cool stars, by means of both observed and synthetic spectra.

We conclude that the NaI infrared feature can be used as a dwarf/giant indicator. We propose a modified definition of the NaI index by defining a red continuum at λ8234 Å and by measuring the equivalent width in the range 8172 - 8197 Å, avoiding the region at $\lambda >$ 8197 Å which contains VI, ZrI, FeI and TiO lines.

Subject Headings: stars: atmospheres, galaxies: stellar content, spectroscopy

1. Introduction

The contribution of M dwarfs to the integrated spectra of galaxies still is a matter of debate. In the near-infrared, one may expect to detect most of the contribution from M-type stars to the integrated light of galaxies. Investigations in this spectral range have involved a number of gravity sensitive indices, such as the NaI doublet ($\lambda\lambda$ 8183 and 8195Å), the Wing-Ford band of FeH (λ 9900Å), the CaII triplet ($\lambda\lambda$ 8498, 8542 and 8662Å) and the CO band at 2.3μm. Based on observations of the NaI doublet at λ8183, λ8195 Å, Spinrad & Taylor (1971, hereafter ST) suggested the presence of a strong dwarf component in M31 and M81. Whitford (1977) used the gravity discriminator FeH Wing-Ford band to conclude that the ST suggestion could not be confirmed. Cohen (1978) observed the infrared NaI doublet, CaII triplet, FeH and TiO bands in M31 and M32, concluding that no enhancement of cool dwarf population is required to explain these features, but that instead, the effect seen is due to the higher metallicity of M31 relative to M32. Faber & French (1980, hereafter FF80) have used the intensity of this feature as an indicator of dwarf/giant ratio, returning to the same conclusion of ST: an excess of M dwarfs in M31. The question was further studied by Persson et al. (1980) through the observation of CO and H_2O narrow-band indices in M31, having measured the indices from the bulge to the nucleus; the CO data do not support a dwarf-enriched nucleus, but the infrared data and the NaI feature are consistent with a metallicity increase of a factor 3 between the bulge and the semistellar nucleus.

Alloin & Bica (1989, hereafter AB89) studied the behavior of this feature in individual stars and in the integrated light of stellar clusters and galaxies. They concluded that the enhancement of the feature in galaxies is due to another absorber, possibly a TiO bandhead

at $\sim \lambda 8205$ Å. Xu et al. (1989) claimed that this feature is actually a blend of TiO, FeI and MgI lines which are observed in metal-rich systems.

Regarding the use of the NaI feature in other external galaxies, Boroson & Thompson (1991) found strong evidence that points to a dwarf-dominated light in NGC 4472, suggesting that population gradients may be present. Delisle & Hardy (1992) observed 10 bulges of spirals and ellipticals in the spectral range 8000-10000 Å, concluding again that the NaI feature is probably a result of a blend and that a metallicity effect may be present. Couture & Hardy (1993) studied the Wing-Ford band in six galaxies concluding that M dwarfs cannot contribute to more than 20% of the I-luminosity of their sample galaxies.

Therefore the interpretation of the NaI λ 8190 Å feature in galaxies is surrounded by a controversy, whether it is predominantly a dwarf/giant ratio indicator or a metallicity sensitive feature. In an attempt to solve this question, we investigate in detail the behavior of the NaI feature through the observation of cool dwarf and giant stars, and by computing synthetic spectra for a grid of stellar parameters, employing updated model atmospheres.

In Sect. 2 the observations are reported. The calculations of synthetic spectra are described in Sect. 3. In Sect. 4 the behavior of the NaI feature as a function of stellar parameters is shown. In Sect. 5 the results are discussed.

2. Observations

The observations were carried out in February/1996 at the 1.5m and 1.4m telescopes of the European Southern Observatory (ESO), La Silla, Chile. At the 1.5m telescope, the Boller & Chivens spectrograph was used with a grating of 1200 l/mm (ESO grating # 11), yielding a dispersion of 66 Å/mm and a resolution of $\Delta\lambda \approx 2$ Å (1 Å/pixel). The Ford Aerospace ESO CCD # 24, of 2048x2048 pixels and pixel size of 15x15 μm was used, and a wavelength coverage of $\lambda\lambda$ 8080-10100 Å was obtained.

The spectral types of the sample stars range from M0 to M7. The sample stars are reported in Table 1, where the visual magnitudes, colours, spectral types and temperatures are indicated. The temperatures were derived by using spectral types vs. temperature calibrations by Fluks et al. (1994) for giants, and a (R-I)$_{Cousins}$ vs. temperature calibration by Bessell (1991) for dwarfs.

In Figs. 1a and 1b are displayed spectra of giants and dwarfs respectively, ranging in temperature from spectral types M0 to M7.

The giant HR3099 was also observed at high resolution at the ESO 1.4m Coudé Auxiliary Telescope (CAT). The Loral/Lesser CCD ESO # 38 with 2688x512 pixels, with pixel size of 15x15 μm was used, at a resolution of R = 45000.

3. Calculations

The code for spectrum synthesis calculations is described in Barbuy (1982), where the computation of molecular lines was included in the code RAI11 from M. Spite. The model atmospheres employed are from Kurucz (1992) for Teff > 3500 K, Plez et al. (1992) for M giants of 2500 < Teff < 3600 K and Allard & Hauschildt (1995) for M dwarfs of 2500 < Teff < 3500 K. The atomic line list is from Moore et al. (1966) and the oscillator strengths were obtained through a fit to the solar spectrum. The NaI doublet is in fact a triplet but two lines are almost coincident. The atomic constants adopted for the NaI lines were the following: log gf = +0.22, -0.479, +0.477, respectively for NaIλ8183.25, λ8194.79 and λ8194.84 Å (Wiese et al. 1969), and interaction constants of 0.3E-30.

Molecular lines of the TiO $A^3\Phi$ - $X^3\Delta$ γ system and CN $A^2\Pi$ - $X^2\Sigma$ red system were included. For TiO the vibrational transitions in the studied spectral region are (3,4), (4,5) and (0,2), where the line lists were kindly made available by J.G. Phillips. For CN, the vibrational transitions are (7,4), (8,5), (2,0), (3,1) and (4,1), where the lists of rotational lines were adopted from Davis & Phillips (1963). Further details on the molecular constants used are described in Erdelyi-Mendes & Barbuy (1991) and Milone & Barbuy (1994).

In order to verify the reliability of our spectrum synthesis, we show in Fig. 2 the fit of the synthetic spectrum computed with ($T_{\rm eff}$, log g, [Fe/H], v_t = (3100 K, 4.5, 0.0, 1.0 km.s^{-1}) to the observed spectrum of the dwarf GL 493.1.

4. Grid of synthetic spectra

We have computed a grid of synthetic spectra in the wavelength range $\lambda\lambda$ 8080 - 8320 Å, for the stellar parameters reported in Table 2.

The equivalent widths of the NaI λ 8190 Å feature were measured in two wavelength ranges: $\lambda\lambda$ 8172-8209 Å (EW_1), as adopted by FF80 and AB89, and $\lambda\lambda$ 8172-8197 Å (EW_2), where essentially only the NaI doublet lines are measured. The red continua are different in the two measurements: the red continuum point adopted by FF80 and AB89 fall onto the bottom of a TiO band, and for this reason we used a better defined continuum point at λ 8234 Å; the two continua definitions can be seen in Fig. 3. In Table 3, the wavelengths of NaI indices and continua are given. Note that the continua defined by FF80 are only given in their Fig. 2, from which we deduced the ranges given in our Table 3 for their definitions of EW_1.

In Figs. 4a and 4b are plotted the equivalent widths of the NaI feature adopting the NaI index definitions EW_1 and EW_2 respectively, for giants and dwarfs, in the range of

temperatures 2500 < T_{eff} < 5500 K. In these Figs. are also illustrated shifts in equivalent widths, in the temperatures of overlap, between the models by Allard & Hauschildt (1995), Plez et al. (1992) and Kurucz (1992). It is evident from Fig. 4b that the NaI feature is clearly stronger in dwarfs of $T_{eff} \lesssim 4000$ K, indicating that the feature can in fact be used as a reliable indicator of the presence of cool dwarfs in composite systems.

4.1 Contaminating features at λ 8197-8205 Å

The TiO bandhead of the vibrational transition (0,2) of the $A^3\Phi$ - $X^3\Delta$ γ system at λ8205 Å is clearly present in giants of $T_{eff} \lesssim 3800$ K, becoming increasingly stronger than the NaI lines for decreasing temperatures. For such low temperatures we also note that the TiO band weakens for higher gravities.

Atomic lines are also present redwards of the λ8197 Å and they become stronger for cooler stars, as already proposed by Xu et al. (1989).

The high resolution spectrum of HR 3099 is shown in Fig. 5, together with the identification of the stronger lines; in this Fig. the synthetic spectrum computed for (T_{eff}, log g, [Fe/H], v_t) = (3750 K, 1.5, 0.0, 2.0 $km.s^{-1}$) is also superimposed. Notice that this temperature is higher than the one indicated in Table 1 (derived from spectral type) for HR 3099, suggesting that this star could be classified as M2 rather than M6.

On the basis of our higher resolution spectra and our spectrum synthesis computations, we confirm the presence of contaminating lines due to atomic lines of FeI, VI and ZrI and a TiO bandhead (Fig. 5). For giants of T_{eff} < 3600 K the TiO band dominates the blend.

5. Discussion

The response of the NaI doublet to the variation of surface gravity is pronounced (Fig. 4b). We conclude that the doublet can be used as a dwarf-giant discriminator. As shown in Figs. 4a and 4b, both definitions of the NaI index (EW_1 and EW_2) can discriminate between dwarfs and giants. We note however that EW_1 includes the bottom of the TiO (0,2) bandhead; in a giant, the total EW_1 will be more due to TiO than to the NaI feature, as shown in Fig. 3. The fact of measuring TiO rather than the NaI lines makes EW_1 slightly sensitive to temperature (and metallicity) for giants, and it introduces a difficulty to disentangle gravity from temperature effects.

For these reasons we propose the index EW_2 which adopts an integration of the line profile in the range λλ 8172-8197 Å; we also suggest the use of a long wavelength continuum

window different from the one previously used (we suggest $\sim \lambda$ 8234 Å), but in fact both continua definitions give a similar dwarf/giant discrimination.

Several authors suggested that the enhancement of the NaI feature in the integrated spectra of some galaxies is due to a higher metallicity, rather than due to a dwarf dominated population. The NaI index, as defined in the literature, is somewhat affected by TiO bands: high metallicity stars are cooler, favoring the strengthening of TiO bands, so that in an indirect way, an enhancement of the NaI feature could be assigned to metallicity.

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Table 1 - Log-book of observations

star	V	Sp.T.	T_{eff}	star	V	Sp.T.	T_{eff}
Giants				Dwarfs			
HR 1693	5.68	M6	3300	GL 190	10.3	M4	3250
HR 2156	6.95	M6	3300	GL 229	8.14	M1e	3630
HR 2168	5.31	M2	3810	GL 273	9.85	M3.5	3220
HR 2469	5.19	M0	3900	GL 285	11.2	M4.5e	3140
HR 2802	5.87	M4	3570	GL 357	10.92	M3	−−
HR 3099	6.33	M6	3300	GL 406	13.45	M6	−−
HR 3816	6.1	M6 − 7epv	3220	GL 493.1	13.4	M5	3090
HR 3793	5.88	M2	3810	GJ 1142A	12.56	M6	−−
HR 4045	6.3	M4 − 5	3500				
HR 4267	5.81	M5.5	3370				

Table 2 - Stellar parameters adopted

models	T_{eff}	log g	[Fe/H]
Kurucz	3500 to 5000	$1.0, 4.5$	$+0.5$ to -2.0
Plez	2750 to 3400	-0.5 to 1.5	0.0
Allard	3500 to 2700	5.0	$+0.5$ to -3.0

Table 3 - Wavelengths defining continua and NaI index

	blue cont.	NaI index	red cont.	designation
FF80/AB89	8169 − 8171	8172 − 8209	8209 − 8211	EW_1
present work	8171.5 − 8172.	8172 − 8197	8233.5 − 8234.2	EW_2

FIGURE CAPTIONS

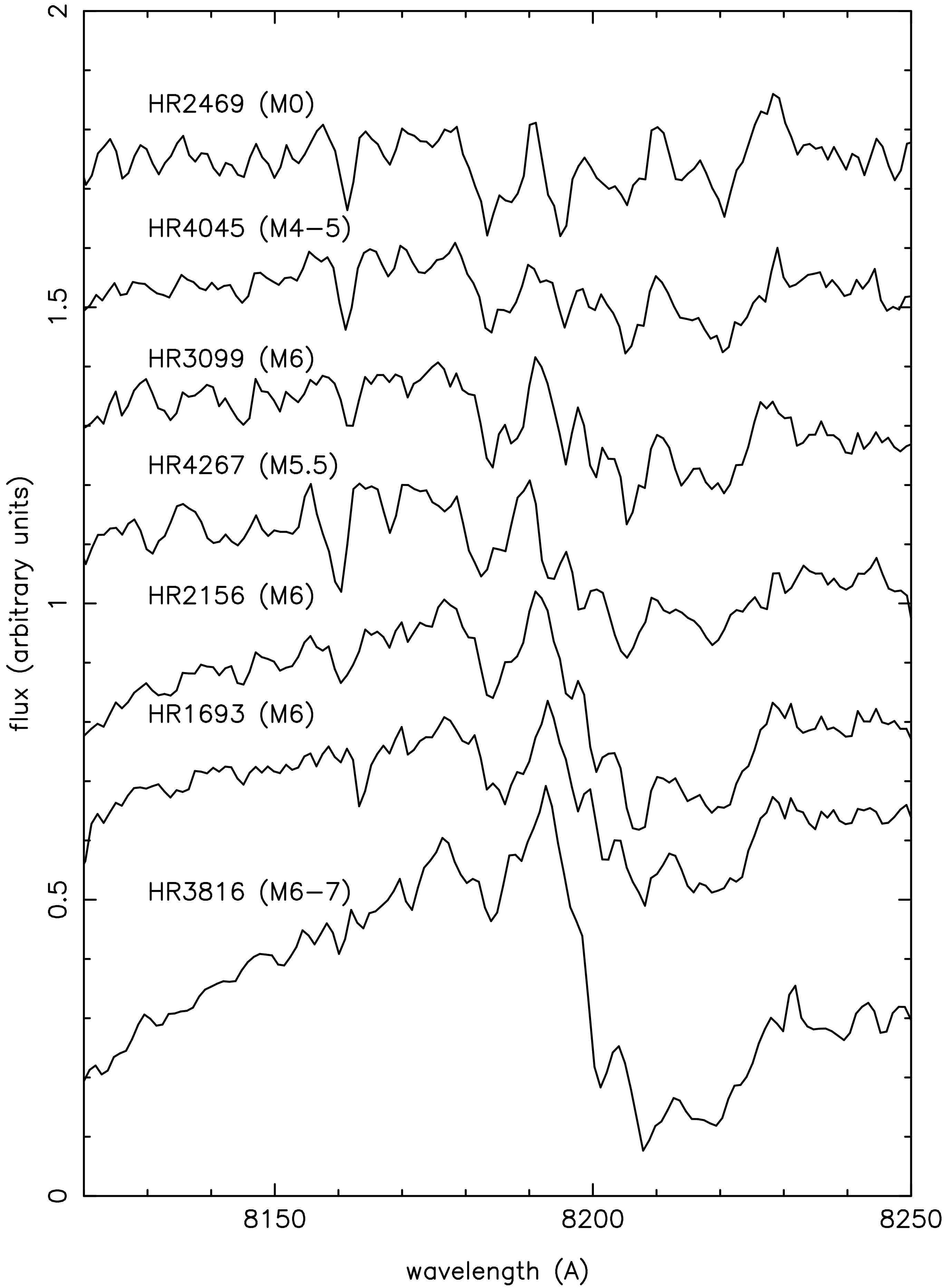
Figure 1 - Observed spectra in order of decreasing temperatures from top to bottom for (a) giants: HR2469 (M0), HR4045 (M4-5), HR3099 (M6 - see Sect. 4.1), HR4267 (M5.5), HR2156 (M6), HR1693 (M6), HR3816 (M6-7); (b) dwarfs: GL229 (M1), GL357 (M3), GL190 (M4), GL493.1 (M5), GL406 (M6).

Figure 2 - GL 493.1: observed spectrum (dashed line) and synthetic spectrum (solid line) computed with (T_{eff}, log g, [Fe/H], v_t) = (3100 K, 4.5, 0.0, 1.0 $km.s^{-1}$).

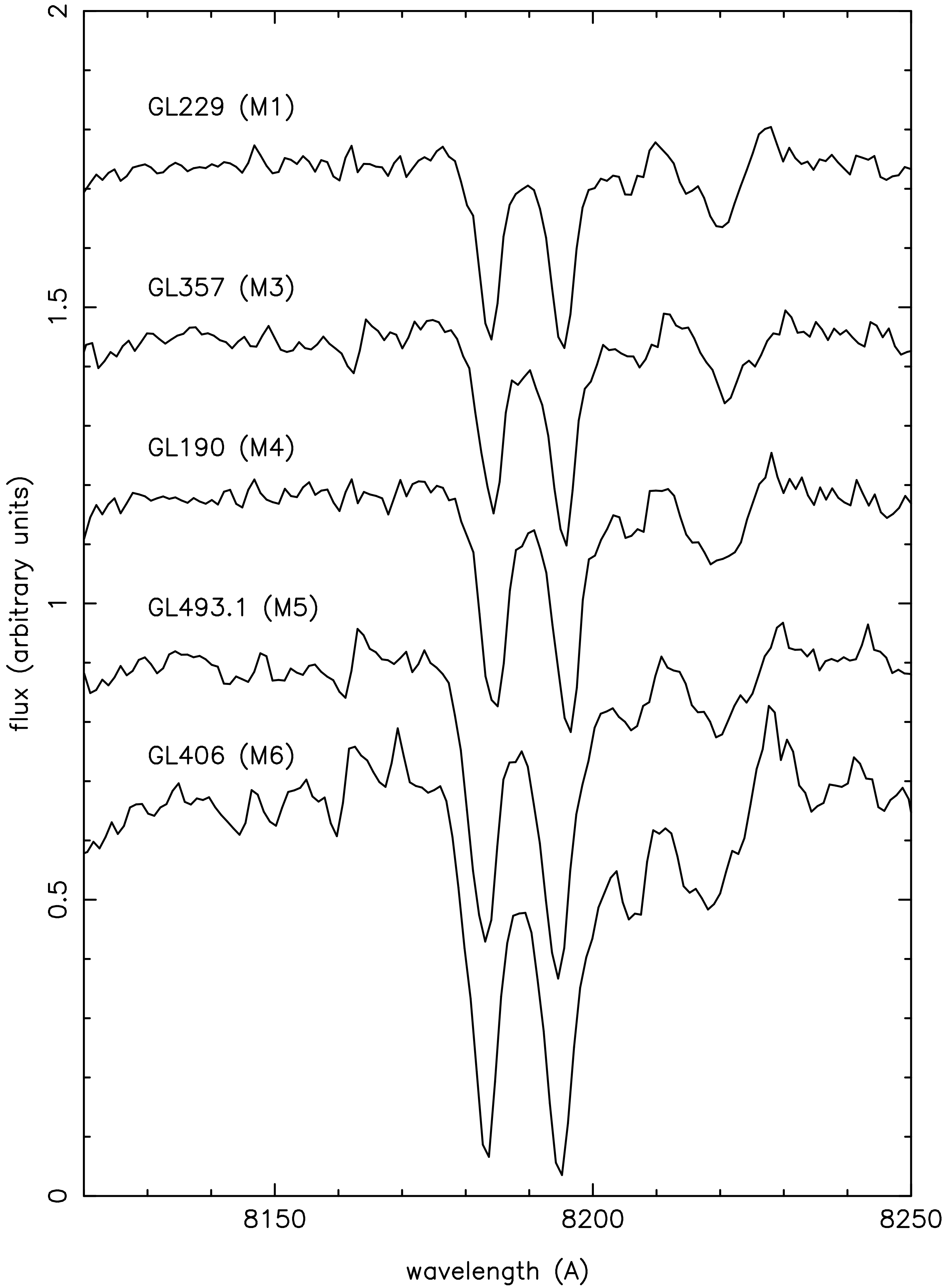
Figure 3 - Synthetic spectra for a dwarf and a giant, where the continuum defined in the literature (lower line) and our adopted continuum (upper line) are indicated.

Figure 4 - Equivalent widths of the NaI feature, for giants and dwarfs, adopting the NaI index definitions (a) EW_1 (present work) and (b) EW_2 (literature).

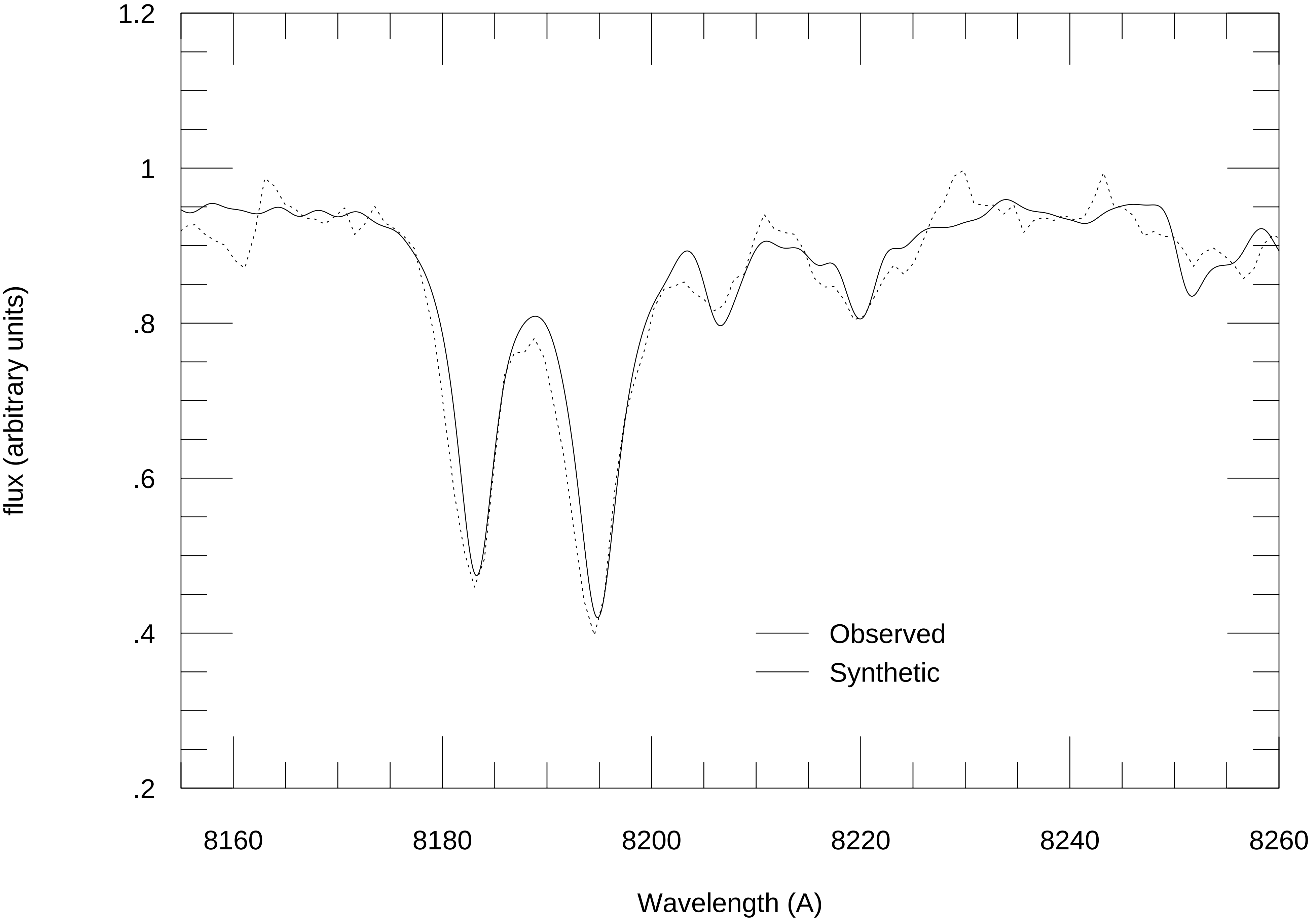
Figure 5 - High resolution spectrum of HR3099 (dotted line), synthetic spectrum computed for (T_{eff}, log g, [Fe/H], v_t) = (3750, 1.5, 0.0, 2.0) (solid line). The main lines are identified.



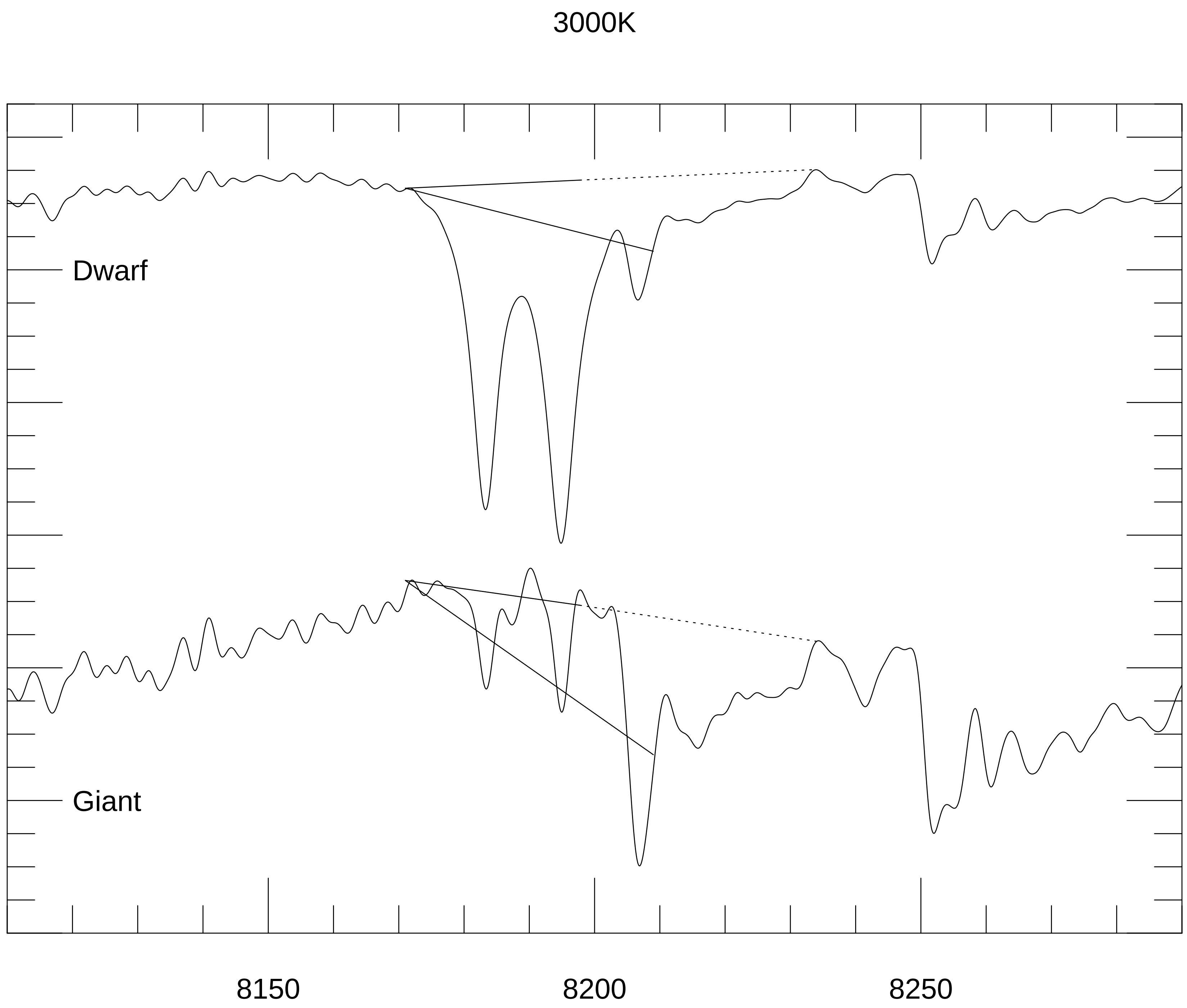
HR2469 (M0)
HR4045 (M4−5)
HR3099 (M6)
HR4267 (M5.5)
HR2156 (M6)
HR1693 (M6)
HR3816 (M6−7)
flux (arbitrary units)
wavelength (A)
0
0.5
1
1.5
2
8150
8200
8250

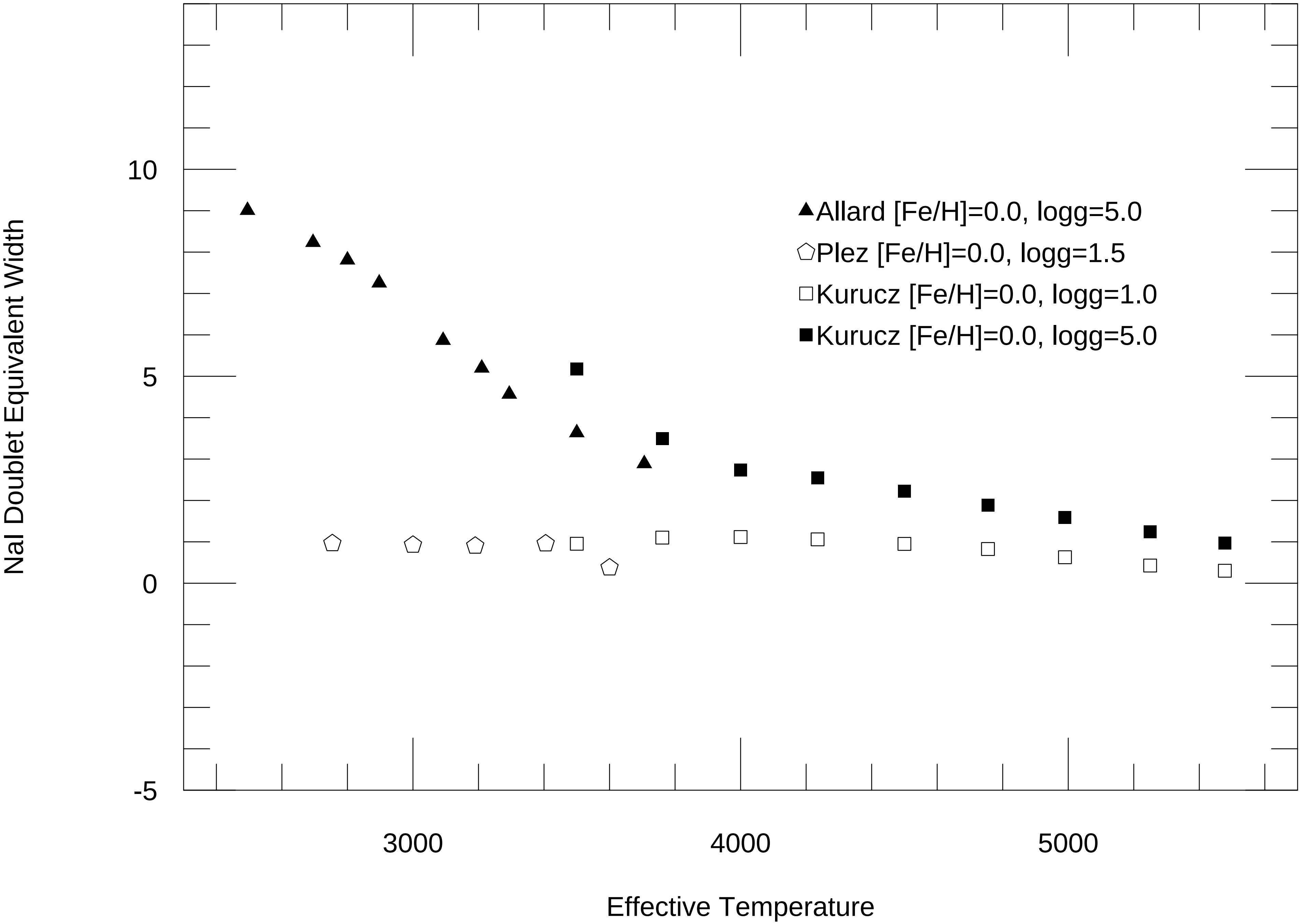


GL229 (M1)
GL357 (M3)
GL190 (M4)
GL493.1 (M5)
GL406 (M6)
flux (arbitrary units)
wavelength (A)
0
0.5
1
1.5
2
8150
8200
8250

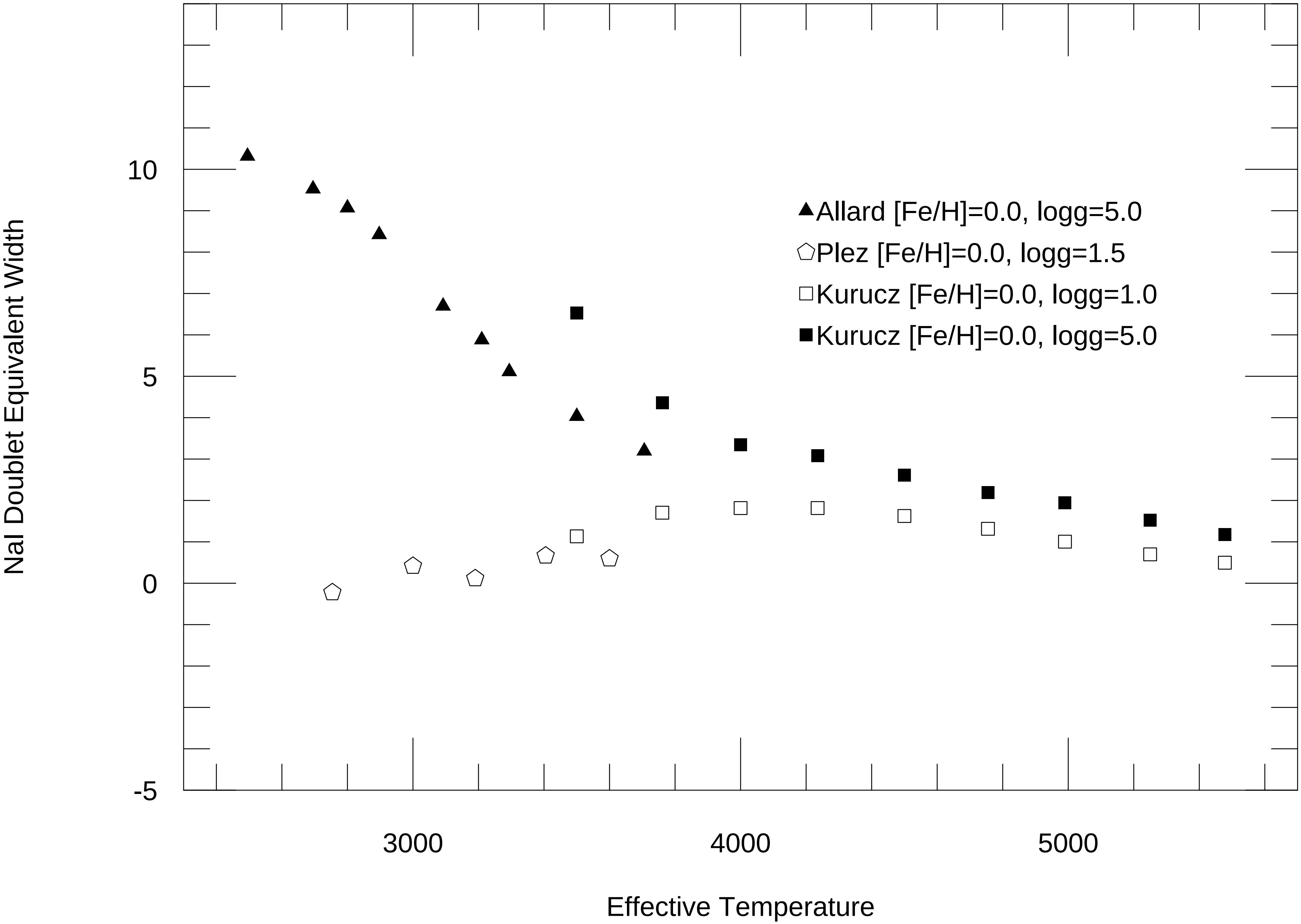


1.2
1
.8
.6
.4
.2
flux (arbitrary units)
8160
8180
8200
8220
8240
8260
Wavelength (A)
Observed
Synthetic

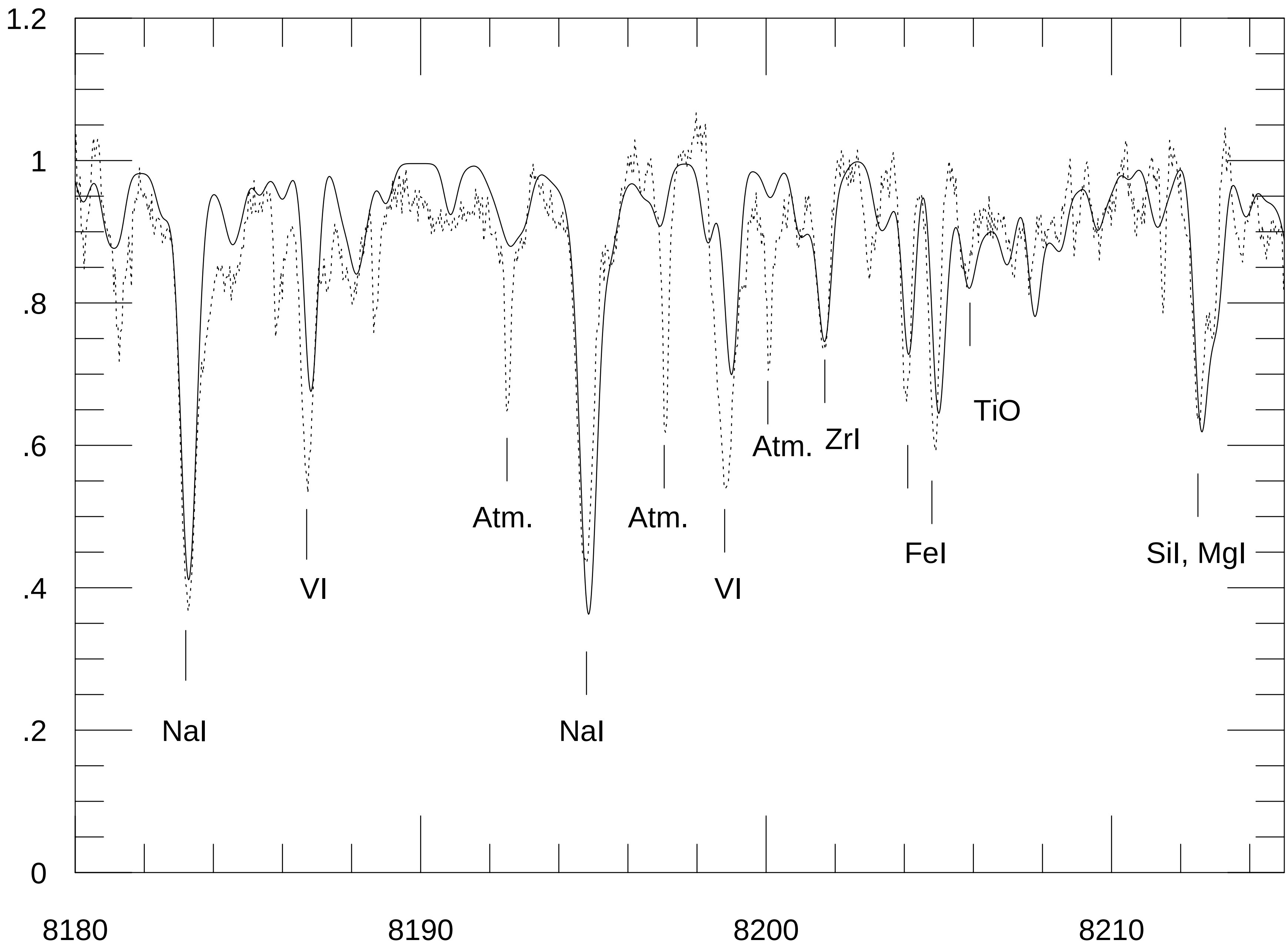

3000K
Dwarf
Giant
8150
8200
8250



Allard [Fe/H]=0.0, logg=5.0
Plez [Fe/H]=0.0, logg=1.5
Kurucz [Fe/H]=0.0, logg=1.0
Kurucz [Fe/H]=0.0, logg=5.0
NaI Doublet Equivalent Width
10
5
0
-5
3000
4000
5000
Effective Temperature



Allard [Fe/H]=0.0, logg=5.0
Plez [Fe/H]=0.0, logg=1.5
Kurucz [Fe/H]=0.0, logg=1.0
Kurucz [Fe/H]=0.0, logg=5.0
10
5
0
-5
3000
4000
5000
NaI Doublet Equivalent Width
Effective Temperature


1.2
1
.8
.6
.4
.2
0
8180
8190
8200
8210
NaI
VI
Atm.
NaI
Atm.
VI
Atm.
ZrI
FeI
TiO
SiI, MgI